

ORBIT DETERMINATION RESULTS AND TRAJECTORY RECONSTRUCTION FOR THE CASSINI/HUYGENS MISSION

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ABSTRACT

During Cassini's third orbit around Saturn, the Huygens Probe was successfully released on a trajectory that resulted in the probe entering Titan's atmosphere on 14-January-2005, making it both the most distant spacecraft landing and the first spacecraft to successfully land on the moon of another planet. The navigation requirements for the probe that had to be met included the flight path angle ($-65^\circ \pm 3^\circ$ at the 99% confidence level) and the angle of attack (less than 5° at the 99% confidence level). Considering that there was no control of the probe after release and that the probe was released 21 days before entry, which was before Saturn apoapsis and before a 127,000 km flyby of Iapetus, the most stringent navigation requirement on the probe was the flight path angle. However, the reconstructed estimate of $-65.4^\circ \pm 0.7^\circ$ (99%) shows that the probe was delivered well within the entry angle corridor. Additional navigation requirements were imposed on the Cassini orbiter to ensure that the orbiter's pointing was accurate enough to maintain the telemetry link from Huygens to Cassini for the probe relay. The navigation contribution to this pointing error could not exceed 3.0 mrad (at the 99% confidence level). The reconstruction indicates that the maximum navigation induced pointing error during the probe relay timeframe was 1.2 mrad with a 0.03 mrad uncertainty (99%).

The dynamic modeling of the spacecraft, satellites, and planet, along with the measurement modeling used in the orbit determination reconstruction are described. Emphasis is placed on the unique modeling and estimation techniques required for handling the probe mission. The satellite, planet and orbiter ephemerides were reconstructed for the 24-November-2004 through 16-January-2005 time span; the reconstruction span for the probe ended at the probe interface time on 14-January-2005. These reconstructions are used as a metric against which the navigation predictions and maneuver execution errors are compared, thus providing insight into the accuracy of the operational orbit determination deliveries.

1. INTRODUCTION

This paper documents the reconstruction of both the orbiter (Cassini) and probe (Huygens) trajectories spanning the second and third Titan flybys, referred to

as the Titan-B (Tb) and Titan-C (Tc) encounters, which occurred on 13-Dec-2004 and 14-Jan-2005, respectively. Significant events during this orbital arc include the Tb flyby, a non-targeted Dione flyby, the probe release, a non-targeted Iapetus flyby, as well as the probe entry and relay that occurred during the Tc flyby. This paper will describe how these events were successfully completed from a navigation point of view and give insight into how well the operational Orbit Determination (OD) used in preparing for these events performed by comparison to this OD reconstruction. A listing of the significant events that occurred during this arc is given in Table 1.

Table 1: Significant Events

Event	Date/Time
Start of Data Arc	24-Nov-2004 00:00
Probe Battery Depassivation	05-Dec-2004 03:54
Titan-B Periapse	13-Dec-2004 11:38
Dione Periapse	15-Dec-2004 01:41
Saturn Periapse	15-Dec-2004 05:51
OTM008 (Probe Targeting Man.)	17-Dec-2004 01:22
OTM009 (PTM-cleanup)	23-Dec-2004 00:52
Probe Release	25-Dec-2004 02:00
Orbiter Detumble	25-Dec-2004 02:05
1 st Optical Images of Probe	25-Dec-2004 14:19
2 nd Optical Images of Probe	26-Dec-2004 13:41
3 rd Optical Image of Probe	27-Dec-2004 13:46
OTM010 (Orbiter Deflection Man)	28-Dec-2004 00:37
Iapetus Flyby	31-Dec-2004 18:49
OTM010a (ODM-cleanup)	03-Jan-2005 23:38
Transition to RCS for Probe relay	06-Jan-2005 18:13
Probe Relay – probe interface time	14-Jan-2005 09:06
Titan-C Periapse	14-Jan-2005 11:12
Completion of Probe Relay	14-Jan-2005 12:06
End of Data Arc	16-Jan-2005 09:20

The Tb flyby was targeted to occur at an altitude of 1200 km on 13-Dec-2004 at 11:39:17.0 ET. From this reconstruction, the flyby occurred at an altitude of 1192 km at 11:39:19.5 ET. Relative to the predicted control dispersions, the 3-D Tb flyby error was 0.3-sigma.

The probe was delivered to the interface altitude (1270 km above Titan) within all requirements [1]. The achieved entry angle of $-65.4^\circ \pm 0.3^\circ$ (1-sigma) was well within the requirement of $-65.0^\circ \pm 3^\circ$ (at the 99% confidence level). Likewise, the angle of attack requirement of $0.0^\circ \pm 5.0^\circ$ (3-sigma) was met, with the reconstructed value being 1.4° .

The orbiter-to-probe pointing requirements during the probe relay were also successfully met. The orbiter pointing accuracy requirement for three hours starting at the interface time was 6.0 mrad (99%). This requirement was sub-allocated between AACS (4.0 mrad) and Navigation (3.0 mrad). The maximum pointing offset between the reconstructed trajectory and the reference trajectory that the onboard pointing profile was based on is 1.22 mrad. The maximum uncertainty in this difference is 0.01 mrad.

2. TRACKING DATA

The radio metric tracking schedule was such that one pass-per-day of X-band range and two-way coherent Doppler was available from the arc epoch until just before the Tb flyby. There was a gap in radio metric tracking of approximately 1.5 days during the Tb flyby, since the spacecraft was off Earth point while it was collecting the various science data. For the most part, after the Dione flyby, two-passes of radio metric tracking data per day were available. The exceptions to this are a couple of days around probe separation when continuous tracking was available, around the Iapetus flyby when there was a 2 day period with only one tracking pass, and continuous tracking from 6-Jan-2005 until the orbiter turns toward the probe for the probe relay on 14-Jan-2005. The tracking complexes in Goldstone and Madrid provided the majority of the coverage, with Canberra tracking during periods with continuous coverage.

The Doppler and range data were weighted on a pass-by-pass basis, based on the noise in the data. The weights are assigned to be equal to the RMS of the residuals times a scale factor of 3.36. Although 1-way and 3-way Doppler data was available at various times, only one pass of 3-way data was used in the solution. This pass was used to provide coverage during the beginning of the probe battery depassivation activity, which, to remain within power allocations, involved spinning down the reaction wheels and transitioning the spacecraft to RCS control.

Optical navigation images (OpNavs) of the satellites were also processed, although there were more gaps in the OpNav coverage than normal because of the significant amount of time that the spacecraft remained Earth pointed in support of the probe mission. The first satellite OpNav was on 24-Nov-2004 05:07 UTC and the last one occurred on 27-Dec-2004 18:00 UTC. The satellites are weighted using an algorithm that accounts for the range from the spacecraft to the body and the particular body in the image [2]. The background stars are weighted using an algorithm that accounts for the pixel DN levels around the star [2]. Minimum weights of 0.25 and 0.1 pixels are used for satellites and stars,

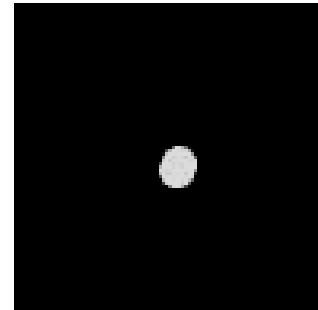
respectively. Table 2 shows the number of OpNavs collected per satellite.

Table 2: Breakdown of Satellite OpNavs

Satellite	Number	Satellite	Number
Mimas	18	Rhea	21
Enceladus	12	Titan	9
Tethys	9	Hyperion	7
Dione	14	Iapetus	13

Images of the probe taken by the orbiter in the few days after separation and before the orbit deflection maneuver (ODM) were also successfully obtained and processed. These OpNavs were valuable in helping to provide separation between the estimates for the release ΔV and the orbiter detumble ΔV . The combination of the release and detumble ΔV s introduced a large uncertainty in the location of the probe relative to the orbiter, which made getting the first image of the probe a challenge. The first set of images was a 5x5 mosaic of wide-angle camera (WAC) pictures taken 12 hours after separation, the mosaic was taken to increase the odds of successfully capturing the probe in the images. Since the images in the mosaic have a slight amount of overlap, it turned out that the probe appears in two of the images (the center image and the next one below it). On the following day, the WAC images were processed and the increased knowledge of the probe position relative to the orbiter allowed the use of the narrow-angle camera (NAC) to image the probe. A couple of WAC images were also taken to alleviate concerns about the instability of the operational OD solution at that time. The final probe OpNav was taken on the following day (27-Dec-2004) using the NAC. This resulted in a total of 4 WAC probe OpNavs and 2 NAC OpNavs. The WAC probe OpNavs are given a weight of 0.25 pixels, while the NAC probe OpNavs are assigned a 1.00 pixel weight. The WAC images were given a tighter weight because they were on the order of 1 to 3 pixels across, which made finding the center of the image less difficult. Meanwhile, the NAC images were more extended (measuring from 5 to 9 pixels across), making it more difficult to locate the center of the image.

Figure 1: Probe OpNav (26-Dec-2005, NAC)



3. ESTIMATED PARAMETERS

Since this arc contained the probe release, there are several parameters that are modeled and estimated which are unique to this reconstruction. That being said, much of the modeling and estimation schemes are very similar to what has been done in previous arcs. The main difference between this arc and others is that the trajectory of both the probe and orbiter are computed with every iteration, from the arc epoch until the end of the arc, which for the probe is only meaningful until the probe reaches the interface altitude on 14-Jan-2005. The two trajectories are forced to be identical until the time of probe release. To ensure that the probe and orbiter trajectories are identical until release, they are initially modeled identically and all estimated parameters are applied to both models through release. The release ΔV is applied to the orbiter and probe in opposite directions, with the magnitude of the ΔV s on each body scaled by the mass ratio between the probe and the orbiter, so that linear momentum is conserved. After release, all of the usual Cassini-specific acceleration models are turned off for computation of the probe trajectory. This includes accelerations that model the internally generated thermal radiation pressure, solar radiation pressure, and stochastic accelerations. Additionally, the small forces and maneuvers that occur after separation are only applied to the orbiter.

The initial conditions for the spacecraft state were interpolated from the previous operational OD arc (Tb arc) at the epoch of 24-Nov-2004 (close to the time of the Saturn apoapsis between Ta and Tb). The Cartesian state of both the orbiter and probe are estimated with the a priori covariance equal to the formal covariance from the Tb arc OD solution with a data cutoff on 24-Nov-2004, scaled by 5. The internally generated thermal radiation acceleration is modeled using a constant acceleration in each of the spacecraft-fixed Cartesian directions, with each component estimated as a bias parameter. The a priori for the estimate of the internally generated thermal acceleration in the spacecraft Z-direction is the solution from the Jupiter to Saturn reconstruction [3], scaled to account for the spacecraft mass loss. Meanwhile, the a priori values for the X and Y components are from pre-launch expectations, scaled in accordance with the observed change in the Z-axis component. Acceleration due to solar pressure is modeled, however no parameters from this model are estimated. During this arc, four maneuvers were performed: the Probe Targeting Maneuver (PTM), the Probe Targeting Maneuver cleanup (PTM-cu), the Orbit Deflection Maneuver (ODM), and the Orbit Deflection Maneuver cleanup (ODM-cu). The ΔV magnitude, right ascension, declination and start time of each of these maneuvers are estimated and the results are presented in the following section. Additionally, the probe release

ΔV is modeled as an impulsive maneuver for both the probe and orbiter. In the filter, the X, Y, and Z components of the release ΔV on the orbiter are estimated, and the release ΔV on the probe is forced to be equal to the orbiter ΔV multiplied by the negative of the mass ratio.

In order to account for mis-modeling of the forces acting on the spacecraft, a set of stochastic accelerations is estimated in each of the spacecraft-fixed coordinates, the batch times and a priori uncertainties of these estimates vary depending on the spacecraft activity. In general, stochastic a priori uncertainties are smallest when the spacecraft is Earth-pointed and under RWA control, and largest when the spacecraft is off Earth-point and under RCS control. Likewise, the batch times are nominally 8 hours in length, but during periods with a lot of spacecraft activity or when the spacecraft is under RCS control, the batch times are reduced.

RCS thrusting activities are modeled as small forces. For the small forces that are pointed in the Earth-line direction, only the ΔV magnitude is estimated, while for many of the other small forces, the right ascension and declination are estimated as well [2]. A total of 28 small forces were modeled and estimated in this solution. During normal operations, the a priori values are predictions obtained from AACS. However, for the RCS thrusting activities associated with both the detumble and post-separation dead-banding, this was impossible since there were no predictions for these events. Therefore, telemetry was used to provide the a priori values. Additionally, the telemetry values for the Tc-flyby RCS turns were used instead of the AACS predictions, since the telemetry values resulted in smaller stochastic acceleration estimates and helped the solution to converge.

The a priori satellite and planet ephemeris used in this reconstruction is JPL ephemeris sat198, with a data cutoff of 24-Nov-2004 applied to the a priori covariance. The estimated satellite parameters include the states (at the epoch of 02-Jan-2004) and GMs for each of the eight satellites. For Saturn, the state, GM, J2, J4, and right ascension and declination of the pole are estimated.

It should be mentioned that the reconstruction estimate for Iapetus GM of $120.54 \pm 0.02 \text{ km}^3/\text{s}^2$ is within the uncertainty of the satellite ephemeris/covariance used during operations for this arc (sat188), which was $120.55 \pm 0.79 \text{ km}^3/\text{s}^2$. Considerable effort was put into coming up with a good estimate for the Iapetus GM before the Tc arc, to reduce its contribution to the entry angle uncertainty for the probe. This was an issue because the Iapetus flyby occurred after the probe was released and any error in the Iapetus mass estimate

would perturb the probe away from the planned trajectory.

There are several parameters associated with the measurement models that are also estimated. A global range bias for each tracking station was estimated with an a priori uncertainty of 1 m. In addition, station range biases are estimated on a pass-by-pass basis with an a priori uncertainty of 3 m. The station locations (~ 3 cm uncertainty), dry and wet troposphere calibrations (1 cm uncertainty each), ionosphere calibrations (1 cm night & 4 cm day), and polar motion (10 cm per axis) are all considered parameters in the filter run. Camera pointing corrections are estimated for each OpNav with an a priori uncertainty of 1 degree in each direction. Finally, Titan 0th and 1st order phase biases are estimated with an a priori uncertainty of 5%.

4. COVARIANCE STUDY COMPARISONS

In preparation for this arc, several covariance studies were performed. In doing these studies in conjunction with the ongoing real time operations it was determined that the planned 64,000 km probe flyby of Iapetus between separation and Tc was too risky. The reason for concern was the uncertainty in the Iapetus GM. Although the formal uncertainties were small enough to not present a problem, the multi-sigma jumps in the estimates of Iapetus GM in ongoing operations was a cause for concern. According to the covariance studies at that time, the Iapetus GM would be known to within $\pm 0.9 \text{ km}^3/\text{s}^2$ (1-sigma), at this level of uncertainty the flight path angle requirement for the probe could have been met. In fact, the covariance studies indicated that there was enough margin to accommodate a $1.5 \text{ km}^3/\text{s}^2$ error in the Iapetus GM. However, at this time we were seeing significantly larger jumps in the Iapetus GM estimates. For example, in late August two successively delivered satellite solutions had the Iapetus GM estimate change from 134.5 ± 4.7 to 118.5 ± 3.7 . An error in the GM on this order would make delivering the probe within the required entry angle corridor unlikely.

Several options were considered to remedy this situation. The first was to delay separation as late as possible. To make this option really viable, it would have been preferable to delay PTM-cu and separation until after the Iapetus flyby, which was impossible because there would not have been enough time to accomplish the ODM and ODM-cu maneuvers before the probe relay activities. A second possible solution was to delay the probe release until the next orbit around Saturn. This alternative was technically viable, since there was no Iapetus flyby during the next orbit. However, this was not a desirable option due to the large impact in altering the early part of the tour. The final option considered, and the one that was chosen,

was to raise the Iapetus flyby altitude in order to reduce the sensitivity of the probe trajectory to the Iapetus GM. This change in the trajectory was accomplished by lowering the target for the Tb flyby altitude from 2200 km to 1200 km, having the effect of raising the altitude of the probe during the Iapetus flyby from 64,000 km to 127,000 km. This significantly increased the available margin for error in the Iapetus GM estimate from $1.5 \text{ km}^3/\text{s}^2$ to $7.2 \text{ km}^3/\text{s}^2$.

In addition to the trajectory change discussed above, a significant amount of effort was put into getting a better handle on the Iapetus GM before the start of this arc. These efforts focused mainly on the 1.1 million km distant flyby that occurred on 17-Oct-2004. This included making sure the spacecraft was in a quiet mode, with no turns or thrusting during the flyby. Also, additional tracking was requested and acquired during this timeframe to maximize the amount of Iapetus GM information captured during the flyby.

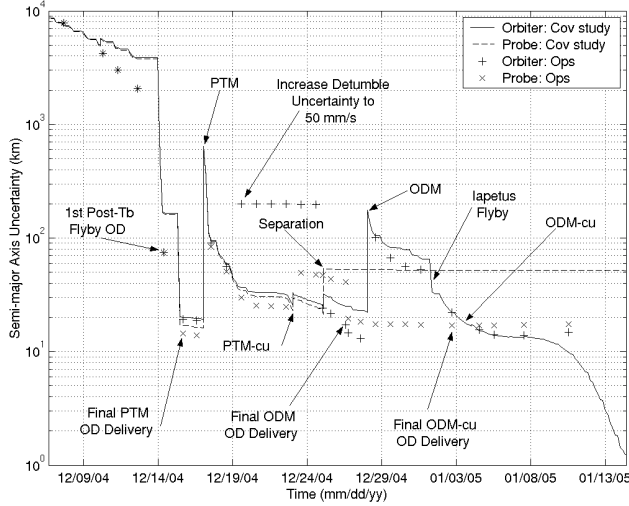
Since the entry angle requirement for the probe was the toughest requirement to meet, it was important to understand what errors were contributing to the entry angle uncertainty. Table 3 gives the error budget from the final covariance study, listed from largest to smallest contributor to the entry angle uncertainty. The data cut-off (DCO) for this error budget is the DCO for the PTM-cu maneuver, since PTM-cu represented the final time to control the probe. From the final line in Table 3, the entry angle 1-sigma uncertainty was predicted to be 0.90° , which meant that the requirement of delivering the probe to an entry angle of $-65.0^\circ \pm 1.15^\circ$ 1-sigma could be met. As shown, the dominant error source was the uncertainty associated with the separation ΔV .

Table 3: Probe Entry Angle 1-Sigma Uncertainty Error Budget

Error Source	Contribution (deg)
Separation (x,y,z = 12 mm/s)	0.74
PTM-cu execution errors	0.31
RCS Events	0.23
Stochastic Accelerations	0.23
OpNav Noise	0.19
RTG Acceleration	0.10
Saturn & Satellite ephemeris	0.08
PTM execution errors	0.08
Radiometric Noise	0.05
S/C state a priori uncertainty	0.04
Earth Orientation Parameters	0.03
Tb approach maneuver	0.02
Media calibration uncertainties	0.02
Range biases	0.02
Station Locations	0.01
OpNav pointing uncertainty	0.00
Titan Phase biases	0.00
RSS	0.90

During operations the covariance studies are typically used as a check to see if we are doing as expected. Figure 2 shows a comparison between the final covariance study results and the official operational OD deliveries. For clarity, the figure only compares the Tc semi-major axis B-plane uncertainties versus time, although similar characteristics can be seen in the other B-plane parameters. For reference, the B-plane is the targeting plane, orthogonal to the inbound asymptote.

Figure 2: Tc B-plane uncertainty comparison between covariance and operational OD solutions



The reasons for the differences between the covariance study and the operations deliveries are for the most part easily explained. Just before Tb, the formal uncertainties were smaller than expected because the Tb approach maneuver was cancelled, thus the associated execution errors were not present in the operational solutions.

Just after PTM, the probe uncertainties dropped to a slightly lower level than expected as a result of two of the future RCS events being cancelled. However, during this same timeframe, the orbiter uncertainties underwent a significant increase due to a change in the a priori uncertainty used for the orbiter detumble ΔV . This uncertainty was increased from 5 to 50 mm/s (spherical), a level equal to approximately 100% of the expected ΔV . This 50 mm/s uncertainty was used until after separation occurred, when the telemetry was used to provide an a priori model for the detumble ΔV and the uncertainty was reduced back to 5 mm/s (spherical).

Between PTM-cu and separation, the probe uncertainties were larger than predicted. In operations the separation uncertainty was applied before the separation actually occurred, while in the covariance study, the separation uncertainty wasn't applied until the time of separation.

After separation, the uncertainties were significantly smaller than predicted, because the covariance study did not include the probe OpNavs. The probe OpNavs were not included in the official covariance study since they were not needed to meet the required accuracy for the probe delivery. However, a considerable effort went into getting these, since it was clear from other covariance studies that the inclusion of the probe OpNavs made a dramatic improvement in the ability of the filter to separate the separation and detumble ΔV estimates.

5. MANEUVER RECONSTRUCTION

This section will document and compare the reconstructed maneuver estimates to the nominal designs for the four maneuvers executed during this arc, in addition to the separation ΔV . Two of the four maneuvers, PTM and ODM, were executed using the main engine, while the PTM-cu and ODM-cu maneuvers were small enough to use the RCS thrusters. Although separation did not involve the use of thrusters, it was modeled as an impulsive maneuver, so the results will be presented here.

Table 4 shows the nominal design and reconstructed estimates for each of the maneuvers. It should be noted that all of the maneuver estimates were sub-sigma relative to the designs. The ODM-cu maneuver had the largest execution errors relative to the design dispersions. This maneuver was an overburn by approximately 4 mm/s, while the 1-sigma uncertainty in the design was 4.4 mm/s.

Table 4: Nominal and reconstructed values and uncertainties

	ΔV (mm/s)	RA (deg)	Dec (deg)	Delay (sec)
OTM008				
Design	11,937.5 \pm 25.9	299.41 \pm 1.10	-78.58 \pm 0.22	0.00 \pm 10.0
Recon.	11,928.6 \pm 5.1	299.29 \pm 0.01	-78.60 \pm 0.02	7.90 \pm 0.1
OTM009				
Design	17.6 \pm 4.1	19.98 \pm 1.40	-10.40 \pm 1.38	0.00 \pm 10.0
Recon.	20.7 \pm 1.9	19.41 \pm 1.12	-10.57 \pm 1.34	0.23 \pm 9.9
OTM010				
Design	23,785.2 \pm 48.6	199.96 \pm 0.21	7.73 \pm 0.20	0.00 \pm 10.0
Recon.	23,793.4 \pm 3.0	200.08 \pm 0.01	7.63 \pm 0.01	8.58 \pm 0.1
OTM010a				
Design	134.7 \pm 4.4	71.16 \pm 2.34	45.61 \pm 1.64	0.00 \pm 10.0
Recon.	138.8 \pm 2.2	72.53 \pm 0.96	45.05 \pm 1.31	-0.13 \pm 3.8
Sep-Orbiter	X (mm/s)	Y (mm/s)	Z (mm/s)	
Design	14.8 \pm 1.3	-34.4 \pm 1.3	-1.5 \pm 1.3	
Recon.	14.0 \pm 0.5	-33.9 \pm 1.0	-2.1 \pm 0.2	
Sep-Probe				
Design	-133.3 \pm 12.0	310.4 \pm 12.0	13.3 \pm 12.0	
Recon.	-125.9 \pm 4.7	305.5 \pm 9.2	19.1 \pm 1.7	

The values at the bottom of Table 4 give the probe release ΔV values in EME2000 coordinates felt by the orbiter and probe, respectively, during separation. The values for the probe assume a mass ratio between the

orbiter and probe of 2885.61 kg / 320.00 kg. The angular difference between the design and reconstruction vectors for the release ΔV is 1.36° , while the difference in magnitudes indicates that the probe felt 7.1 mm/s less ΔV in the reconstruction than the design. The a priori uncertainty used in the filter was taken from the requirement of 35 mm/s (3-sigma).

6. TITAN-B (TB) FLYBY

The Tb flyby was previously documented in the Tb arc reconstruction [4]. Although the trajectory described herein is the official Tb reconstruction, comparisons between the two trajectories will be made to give some insight into the consistency between the two solutions. This provides something besides just the formal uncertainties as a measure of accuracy.

As mentioned earlier, the Tb flyby occurred on 13-Dec-2004 11:39:19.5 ET at an altitude of 1192.3 km, almost 8 km lower than targeted. Table 5 compares the B-plane values and uncertainties from five different cases: the design, a couple of pre-Tb OD deliveries, and the reconstructed values from both the Tb and the Tc reconstruction memos. The design line includes the target and OTM006 dispersion ellipse. The first of the pre-Tb OD deliveries is from the Tb arc, this delivery had a DCO of 08-Dec-2004 05:40 and was the final official OD delivery made from the Tb arc prior to Tb. It would have been the OD delivery used for the Tb approach maneuver (OTM007), if the maneuver had not been cancelled. The second pre-Tb OD delivery shown in the table was made from the Tc arc, and although it has a later DCO than the Tb arc delivery, it still provides a good comparison to the Tb arc pre-Tb delivery. The final two lines in Table 5 show the two Tb reconstructed values, one from the Tb arc and the other from the Tc arc. The 1-sigma uncertainty in altitude of closest approach for both reconstructions is 0.03 km. In a 3-D sense, the Tb reconstruction represents a 0.30-sigma error relative to the OTM006 dispersion ellipse, and a 3.0-sigma error relative to the pre-Tb OD delivery.

Table 5: Tb B-plane comparison

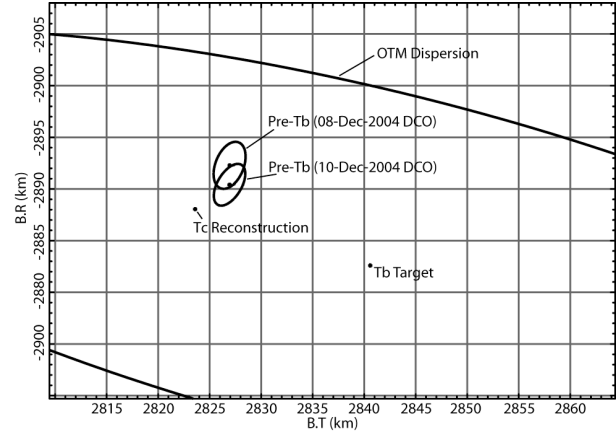
Case	B.T (km)	B.R (km)	SMAx SMI (km)	Altitude (km)	TCA (sec past 11:39)
Design	2840.58	-2882.59	66.62x16.96	1200.00	17.00±11.7
08-Dec	2826.94	-2892.29	2.39 x 1.37	1197.64	19.22±0.26
10-Dec	2826.93	-2890.41	2.25 x 1.17	1196.29	20.18±0.31
Tb Rec.	2823.61	-2888.08	0.04 x 0.03	1192.31	19.44±0.06
Tc Rec.	2823.59	-2888.05	0.04 x 0.03	1192.27	19.54±0.08

Figure 3 graphically shows the B-plane information presented in Table 5. For clarity, the Tb arc reconstruction solution has been left off the plot, since

at this scale it looks identical to the Tc arc reconstruction of Tb.

The primary reason for the shift in the Tb B-plane values between the pre-Tb OD deliveries and the post-Tb solutions, including the reconstructions, is a shift in the Titan state estimate. The reconstructed estimate of the Titan state differed by between 1 and 2-sigma for each of the six state parameters relative to the 10-Dec-2004 OD delivery.

Figure 3: Tb B-plane comparison (EMO 1-Sigma)



7. TITAN-C (TC) FLYBY

The Tc flyby occurred on 14-Jan-2005 11:13:03 ET at an altitude of 60003.3 km, a little more than 3 km higher than targeted. Tc was targeted at such a high altitude to accommodate the probe relay activities. The following section will cover the probe aspect of the Tc flyby.

Table 6 and Figure 4 compare the B-plane results for the orbiter at Tc. The first case is the ODM dispersion ellipse, which was based on an OD delivery with a DCO on 26-Dec-2004, in the plot this is the larger of the two ellipses centered about the Tc target. The second case is the OD delivery that was used to design ODM-cu; this solution has a DCO of 02-Jan-2005. In a 3-D sense, this solution represents a 1.1-sigma error relative to the ODM dispersion ellipse. The third case shows the ODM-cu dispersion ellipse based off of the same OD delivery used in the second case. The last case is the reconstruction, which as shown in both the table and plot is more than 1-sigma away from the target relative to the ODM-cu design in both the B-plane and TCA. In a 3-D sense, the reconstruction represents a 1.8-sigma error relative to the ODM-cu dispersion ellipse. In addition to the ODM-cu errors shown in Table 4, another reason for this error is that there was a significant change in the ODM estimates in the OD solutions after the ODM-cu design DCO. The Right Ascension and Declination values for ODM changed by approximately 1.4-sigma and the ΔV magnitude

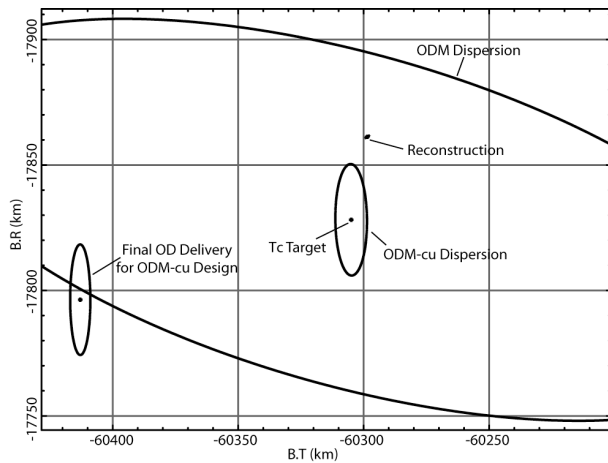
estimate changed by about 0.7-sigma, relative to the final ODM-cu design OD solution estimates. Other greater than 1-sigma differences in the reconstruction relative to the ODM-cu design OD delivery are in some of the small forces events that model the detumble and other activities just after separation.

Table 6: Tc B-plane comparison

Case	B.T (km)	B.R (km)	SMAxSMI (km)	Altitude (km)	TCA (sec past 11:13)
ODM Design	-60304.98	-17828.17	179x66	60000.0	0.0±35.5
ODM-cu OD	-60412.92	-17796.30	22.1x4.0	60094.5	19.8±2.8
ODM-cu Des.	-60304.98	-17828.17	22.2x6.3	60000.0	0.0±2.9
Recon.	-60298.57	-17861.23	1.03x0.09	60003.3	3.0±0.1

It should be noted that the operational OD solutions that were made after ODM-cu slowly began moving towards the reconstruction estimates, so if these B-plane solutions were shown in Figure 4, a trend from the Tc target towards the reconstruction would be apparent. One value of interest, but not shown in Table 6, is the 1-sigma uncertainty in the Tc altitude, which is equal to 0.70 km in the reconstruction.

Figure 4: Tc B-plane comparison



8. THE PROBE RESULTS

Rather than B-plane parameters, the probe was targeted to an entry angle of -65.0° , an altitude of 1270 km, and a B-plane angle of 167.5° at the interface time of 14-Jan-2005 09:07:00 ET. Both maneuvers before separation (PTM and PTM-cu) targeted these parameters. The most stringent requirement to meet from an OD standpoint was the 99% entry angle corridor of $65.0^\circ \pm 3^\circ$ (approximately equivalent to $\pm 1.15^\circ$ in a 1-sigma sense). Table 7 and Figure 5 show how the entry angle and interface time estimates and uncertainties changed from PTM through the ODM-cu OD delivery and finally the reconstruction.

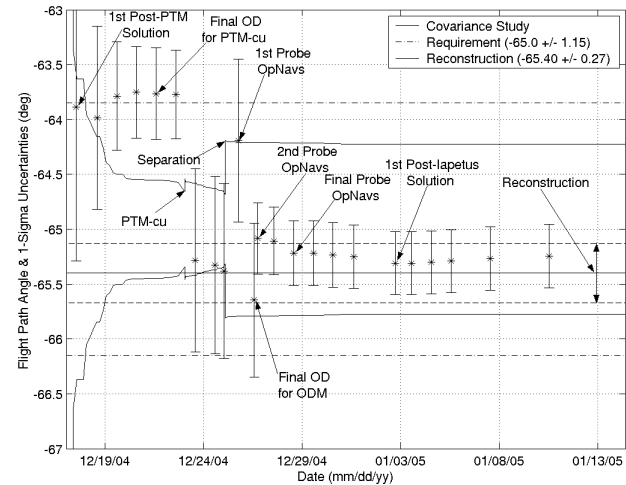
The uncertainties in the final PTM-cu OD delivery are so low because they do not include the uncertainty of separation. From the first two lines in Table 7, the entry angle estimate of -63.76° after PTM was well within the 1-sigma control dispersion for the PTM design.

Table 7: Entry Angle and Interface Time Estimates & 1-Sigma Uncertainties

Case	Entry Angle (deg)	Interface Time (14-Jan ET)	Uncertainty (sec)
PTM Design	-65.00 ± 9.69	09:07:00.00	136.72
Final PTM-cu OD	-63.76 ± 0.41	09:06:55.44	6.92
PTM-cu Design	-65.00 ± 0.89	09:07:00.00	13.92
Final pre-sep OD	-65.33 ± 0.81	09:06:55.45	12.57
Final ODM OD	-65.65 ± 0.70	09:06:49.97	15.87
Final ODM-cu OD	-65.31 ± 0.29	09:06:58.54	6.16
Reconstruction	-65.40 ± 0.27	09:06:56.71	5.82

Note that the entry angle uncertainty did not drop significantly and the interface time uncertainty actually rose between the final pre-separation OD delivery and the final ODM OD delivery. This is a result of the a priori separation uncertainty being scaled by three immediately following the probe release because of some confusion with the AACS reconstruction of the separation ΔV , which was quite a bit different than the nominal design. When enough post-separation tracking became available, we became confident that the separation ΔV was actually fairly close to the design and the scale of three was removed from the a priori uncertainty on the separation ΔV . Also from Table 7, the difference between the PTM-cu design and the reconstruction is well within the 1-sigma control dispersions for both the Entry Angle and the Interface Time.

Figure 5: Entry Angle Estimates and Uncertainties vs Data Cutoff

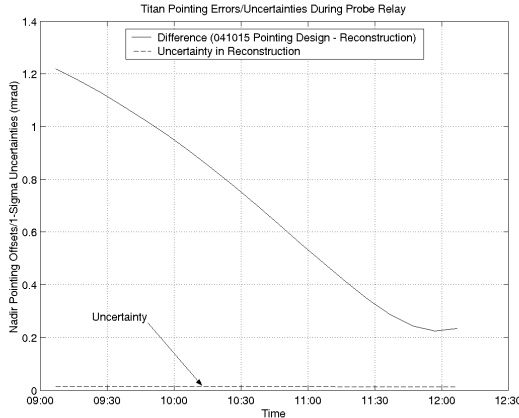


From the reconstruction results, it is clear that the probe was well within the entry angle corridor. Additionally, the other targets were within the requirements. The B-

plane angle was equal to the targeted value of 167.5° . The angle of attack was desired to be less than 5° (99%), it turned out to be equal to 1.44° [5].

Another requirement for the probe mission was for the orbiter to maintain a minimum pointing accuracy of 6 mrad (99%) during the probe relay timeframe, which was defined as three hours starting at the interface time. The 6 mrad accuracy level was split into an AACs allocation and a Navigation allocation. The Navigation allocation was determined to be 3 mrad (99%). The onboard pointing parameters were designed based on the 041015 covariance study delivery (made on 15-Oct-2004). ODM-cu was performed to get the spacecraft relative to Titan trajectory back close to this reference, rather than updating the pointing parameters. Figure 6 shows the difference in pointing between the 041015 design and the reconstruction as well as the pointing uncertainties in the reconstruction during the probe relay time span. The reconstruction pointing uncertainties (the dashed line) are small enough that the difference (the solid line) approximates the amount of pointing error due to the OD used to design the pointing parameters. Since the maximum error during the probe relay time span is 1.2 mrad, the 3 mrad Navigation probe relay pointing requirements were met.

Figure 6: Relay Pointing Errors and Uncertainties



9. ORBITER POSITION UNCERTAINTIES

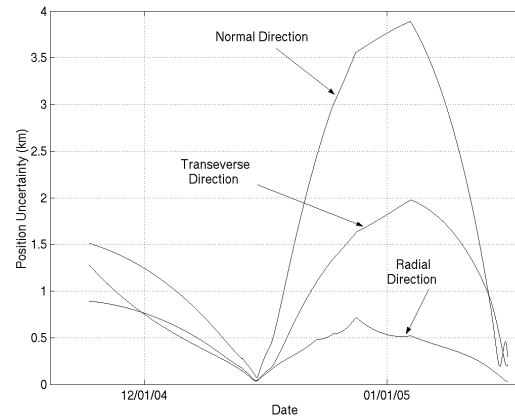
Figure 7 shows the reconstructed position uncertainties for the Orbiter during the Tc arc relative to the Saturn barycenter. As usual, the largest uncertainties occur near Saturn apoapse, while the trajectory is known best near Saturn periapse.

10. CONCLUSIONS

The Navigation goals for the Tc arc were all successfully met. This includes the delivery of the probe within the target constraints and delivering the orbiter accurately enough to meet the probe relay pointing

requirements. Execution errors for all maneuvers were sub-sigma, although the Tc flyby was 1.8-sigma outside the control dispersions for the ODM-cu maneuver. The reasons for this include greater than 1-sigma shifts in both the ODM solution (relative to the ODM-cu design OD delivery) and in some of the small forces just after separation. Additionally, ODM-cu itself was almost a 1-sigma over-burn.

Figure 7: Cassini Position Uncertainties Relative to the Saturn Barycenter



11. REFERENCES

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ACKNOWLEDGEMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Reference to any specific commercial product, process, or service by trade name, trademark, manufacturer or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.